

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 16-03-2007		2. REPORT TYPE Technical Paper and Briefing Charts		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Fully Reusable Access to Space Technology (FAST) Methane Rocket				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Lt Cole Doupe, Jess Sponable, Jeffrey Zweber (AFRL/VA); Richard Cohn (AFRL/PRSE)				5d. PROJECT NUMBER 50260651	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFRL/PRSE 4 Draco Drive Edwards AFB CA 93524-7160				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-PR-ED-TP-2007-108	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRSE 4 Draco Drive Edwards AFB CA 93524-7160				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-PR-ED-TP-2007-108	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited (Public Affairs No. 07105A).					
13. SUPPLEMENTARY NOTES Presented at the 22 nd National Space Symposium, Colorado Springs, CO, 3-6 Apr 2007; and JANNAF 54 th Propulsion Meeting/3 rd LPS/2 nd SPS/5 th MSS Joint Meeting, Denver, CO, 14-17 May 2007.					
14. ABSTRACT This paper provides an overview of the Fully Reusable Access to Space Technology (FAST) program. The program is an Air Force Research Laboratory initiative to methodically mature the technologies required for next generation operationally responsive space access – an Air Force Space Command mission. Program goals and requirements are delineated as well as technology approaches. The acquisition strategy matures key technologies in ground experiments through 2011, and then integrates the experiments into a subscale X-aircraft for ground or potentially flight test by 2013. The airframe experiment includes propellant tanks, structure and thermal protection systems fabricated and tested at the X-aircraft scale. In addition, subsystems experiments shall be accomplished such as a Flight Operations Control Center, avionics, adaptive GN&C, Integrated Systems Health Management, etc. An approach is also identified for either using an off-the-shelf propulsion system or a low cost, high ops tempo propulsion experiment. Key program goals include ensuring component demonstrations are scaleable to larger future operational systems, and that the technology demonstrations directly transition to fabrication and flight test of the experimental flight test vehicle. Potential future applications of the technologies are also briefly reviewed.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Richard Cohn
Unclassified	Unclassified	Unclassified	SAR	42	19b. TELEPHONE NUMBER (include area code) (661) 275-6177

Fully Reusable Access to Space Technology FAST

Lt Cole Doupe
Jess Sponable
Dr. Jeffrey Zweber
Air Vehicles Directorate
Air Force Research Laboratory

Dr. Richard Cohn
Propulsion Directorate
Air Force Research Laboratory

DISTRIBUTION STATEMENT A:
Approved for public release; distribution is unlimited.
Date of Determination: 3/21/2007.
AFRL-WS 07-0646

ABSTRACT

This paper provides an overview of the Fully Reusable Access to Space Technology (FAST) program. The program is an Air Force Research Laboratory initiative to methodically mature the technologies required for next generation operationally responsive space access – an Air Force Space Command mission. Program goals and requirements are delineated as well as technology approaches. The acquisition strategy matures key technologies in ground experiments through 2011, and then integrates the experiments into a subscale X-aircraft for ground or potentially flight test by 2013. The airframe experiment includes propellant tanks, structure and thermal protection systems fabricated and tested at the X-aircraft scale. In addition, subsystems experiments shall be accomplished such as a Flight Operations Control Center, avionics, adaptive GN&C, Integrated Systems Health Management, etc. An approach is also identified for either using an off-the-shelf propulsion system or a low cost, high ops tempo propulsion experiment. Key program goals include ensuring component demonstrations are scaleable to larger future operational systems, and that the technology demonstrations directly transition to fabrication and flight test of the experimental flight test vehicle. Potential future applications of the technologies are also briefly reviewed.

INTRODUCTION

The FAST program vision is pictorially illustrated in Figure 1. The goal of this effort is to mature technology enabling both high speed aircraft and “aircraft-like” space access for future Reusable Launch Vehicle’s (RLV’s). It bears emphasizing that FAST is not developing technology for any single RLV concept, but rather is maturing the materials, structures, subsystems, thermal protection, and propulsion technologies that will be needed by a wide range of potential 21st Century launch concepts. This could include, but is by no means limited to, all-rocket and airbreathing combined cycle propulsion systems, single and multiple stage to orbit, and horizontal and vertical launch and landing systems. Implementing the FAST vision will lead to many advantages over today’s expendable launch systems including: 10X lower recurring flight cost, 10X higher flight reliabilities, and 10-100X faster turn-around and call-up times.

Specific Air Force Research Laboratory (AFRL) objectives in establishing the FAST program include: 1) enabling “aircraft-like” space access capabilities, 2) spinning-off critical 21st Century technologies to both the air and space sectors, 3) helping build a cadre of Air Force technical and management expertise for high speed flight systems, and 4) helping build a healthy U.S. entrepreneurial space access industry that will contribute to future defense needs.

The FAST program is different from many past RLV efforts. The focus is on methodical development of the critical technologies, first via ground experiments and then eventually by integrating the technologies into a subscale X-Aircraft. This effort also seeks to leverage the large amount of data available from the commercial aircraft, UAV, and affordable, low-cost composites technologies into the design process. It is recognized that prudent judgment will be required in order to use the lessons learned from these applications as the space launch market has many unique facets. The commercial entrepreneurial space access sector also offers both an example of how to better control and leverage costs, and a potential customer base for FAST technologies. The difference in mission between these applications and military requirements will be examined at all steps during the process to ensure maximum benefit to both the air force as well as the entrepreneurial space access sector. Figure 2 portrays both the technologies being matured by FAST and how they will feed a flight experiment leading to many different future applications.

The ultimate goal of the program is to fabricate and fly an X-Aircraft. To control costs, the X-Aircraft is about the same physical size as suborbital tourist vehicles being developed by entrepreneurial space access companies. However, unlike these commercial efforts that fly only in the Mach 3+ range, the FAST X-Aircraft is designed to fly in the Mach 4 to 7 range when it takes off from the ground without additional boosters, and in addition can be configured to

reenter from a Mach 25 orbital velocity with a fully reusable thermal protection system when launched from another platform.

FAST FLIGHT EXPERIMENT

The physical size, weights and general layout of the current FAST Flight Experiment design is illustrated in Figure 3. The configuration has a cylindrical fuselage and the baseline X-aircraft takes off vertically and lands horizontally. The cylindrical shape lends itself to staging operations, i.e., it is easy to attach one stage to another. The physical size is roughly half that of the F-15 shown for reference and roughly one third of the F-15's dry weight. A flat base helps ensure stable flight during hypersonic reentry. The wings and tail surfaces are sized first for stable reentry but also for horizontal landing at an acceptable landing speed. Ongoing trades will help define size and orientation of the various control surfaces.

The gross weight and the resulting physical size was determined by sizing the vehicle for a sea level thrust to weight of 1.4 using four commercially available LOX/Methane C&Space CHASE 10 rocket engines. Alternate engine operations, including five PWR RL-10's modified for LOX/Methane or a single LOX/RP SpaceX Merlin engine are being considered. In addition, the program is carrying several low cost, high ops tempo propulsion experiments which their proponents claim could be developed to support the requirements of the FAST effort.

Because the baseline FAST Flight Experiment size limits its ground launched single vehicle flight envelope, the FAST program is also evaluating an option for a larger X-aircraft sized around four SpaceX Merlin engines. This size could support flight test to at least Mach 12 in a ground launched single vehicle flight. This vehicle is also sized approximately to be the booster stage for a hybrid launch vehicle capable of launching payloads of 1 to 5Klbs to low earth orbit. Figure 4 illustrates both the size of the smaller aircraft sized by the 4 CHASE 10 engines and the larger aircraft sized by 4 Merlin engines. The figure highlights that even the larger aircraft is only the size of an F-15, surprisingly small. It also emphasizes the scale of the X-aircraft compared to notional operational system concepts. The figure shows a potential development path to both reusable first and second stages.

Figure 5 portrays the program schedule. AFRL is budgeting approximately \$70 million over the fiscal year defense plan to mature the FAST technologies. The limited funding has driven a technology maturation strategy that emphasizes first accomplishing critical ground experiments. These experiments are sized to support rapid transition to a follow on X-aircraft. The initial ground experiments will be conducted between FY07 and FY11 with follow-on integrated technology experiments being accomplished between FY11 and FY13. The X-Aircraft could fly as early as 2013. As illustrated, the ground experiment phase includes integrated airframe structures, tanks and thermal protections systems. It also

includes subsystems technologies such as flight operations controls/management, adaptive GN&C, and integrated systems health management technology.

After successfully completing the ground experiments, the program will be ready to proceed into development of an integrated X-Aircraft, either on the ground or in a flight experiment. We believe we have adequate funds to complete the ground experiments and the integrated X-Aircraft ground experiment. However, a flight experiment requires additional funding and AFRL is seeking program partners interested in leapfrogging U.S. space access capabilities into the 21st Century. Key flight experiment goals and thresholds are summarized in Table I. The program measures of merit have been established around threshold values that are achievable but challenging, and goal values that are significantly more aggressive, in the words of Collins and Porras, “Big, Hairy, Audacious Goals.”

GROUND EXPERIMENTS

Although the ultimate goal of the FAST program is to accomplish a flight experiment, near term investments are focused on critical enabling ground experiments. The ground experiments are structured to directly support and transition to a follow-on flight experiment, but they will deliver useful, focused technology in their own right. There is nothing like an X-Aircraft, actual or virtual, to help focus the technologist and maximize the delivered product. Put another way, the threat of flight can be a serious motivator.

Figure 6 illustrates the stepping stone approach being taken by FAST to mature critical ground technologies, then integrate them into an X-Aircraft and eventually fly them. The three investment areas identified in the figure are airframe, subsystems and propulsion. Although the details are still being defined, at least notionally each of the experiments is described in more detail in the following paragraphs.

Airframe Experiment. The airframe ground experiment will fabricate and integrate propellant tanks, structure, thermal protection systems (TPS), and a Structural Health Management (SHM) system at or near the same scale as the subscale X-Aircraft. The airframe structure and propellant tanks will be built from affordable composites. The propellant tanks will most likely be integral load bearing tanks, potentially with a common oxidizer/fuel bulkhead to help minimize weight. For the structure and tanks, conventional composites such as graphite epoxy with a temperature capability up to about 350°F and warm composites structures such as graphite-bismaleimide (BMI) or graphite-polyimide with temperature capabilities as high as 700°F are being considered. Although the latter manufacturing processes can be expensive, they offer an obvious and easy block upgrade path as the technologies are fully matured in ongoing laboratory programs. Such warm composite structures could potentially be all that is

required on the leeward and cooler surfaces of the X-Aircraft. Indeed, for some first stage applications such warm structures may never require any external TPS.

On orbital reentry vehicle, such warm structures are also potentially applicable as the internal structure under the external TPS. In this application, they reduce the thickness and therefore weight of required TPS. However, they will not replace the need for external TPS for orbital reentry applications. Significant portions of the aircraft will require such TPS. Fortunately, there is a wide variety of different options available including carbon fiber/carbon matrix (CC) or carbon fiber/carbon-silicone matrix (CSic) hot structures on the windward side and leading edges, potentially with high thermal conductivity CC foams and/or phase change materials on the backside to rapidly dissipate heat. An ongoing AFRL program to mature this kind of “Rainbow TPS” is shown in Figure 5 as the leading edge demo. If fully successful, such approaches could reduce the temperature on the outside of the leading edge material by as much as 300 to 700°F due to rapid 3-dimensional dissipation of heat around the surface. As the FAST airframe experiment matures it may include the Rainbow TPS on the leading edges, or cost considerations may drive the program to evaluate this technology as a future upgrade. In either case, AFRL will continue developing these kinds of “game changing” TPS technologies.

Other portions of the airframe could include metallic TPS, CMC wrapped tiles, AFRSI blankets and many other potential options. As currently envisioned, the TPS used in the FAST experiment will either be a permanent structure that doesn’t require replacement, or it will be mechanically attached using quick connect/disconnect fasteners. Such fasteners are another “game changing” technology that will allow FAST to leverage the huge investment in TPS technologies over the past 30 years, yet potentially achieve the responsive call up and rapid turnaround requirements shown in Table I, i.e., aircraft-like responsiveness. Structural health monitoring would most likely be embedded with the mechanically attached TPS to ensure it stays attached, and to provide health status on other parts of the structure. The above TPS technologies including fasteners and health monitoring are a major focus of ongoing AFRL technology maturation activities by both the AFRL Materials and Air Vehicles Directorates.

One of the key lessons learned from the FAST configuration studies is that the type of TPS and the vehicle location on which it is applied depends on many factors including the external shape of the aircraft, the type and size of control surfaces, and the trajectory used for reentry. A major concern is the stability of the configuration during reentry, from orbital velocities to landing speeds. This issue is compounded by the fact that the FAST RLV is very different from any other aircraft ever flown. The internal propellant tanks drive a relatively large airframe size compared to its dry weight. However, most of the weight is located in the tail of the aircraft (engines, subsystems, etc.). The result is an aft center of

gravity that makes stable flight very challenging, and will likely require the use of Reaction Control System (RCS) propellants to augment stability. The trade between RCS usage and control surface size must be examined to find a reasonable performance solution and an acceptably high Propellant Mass Fraction (PMF). It bears pointing out that this is a generic problem applicable to any RLV that carries propellants internally, and reenters with large empty tanks.

The other major trade that impacts TPS is the reentry trajectory flown, in particular the angle of attack (AOA) at high speed reentry. Using POST, Miniver and CFD analysis the program compared constant AOA reentries at 30, 50, and 70 degrees. The resulting data consistently highlighted that the total heatload (BTUs/ft²) was nearly 4X more at 30 than at 70 degrees. Similarly, the maximum heat flux (BTUs/ft²/sec) and temperature was around 20% higher. From a TPS point of view, there is a major advantage to increasing the AOA and reducing the thermal stress on the aircraft. Unfortunately, nothing is free since high AOA flight compounds stability issues and decreases downrange and cross range trajectory capability. The data simply doesn't exist today to say we can or cannot fly safely at high AOA. To overcome this limitation the X-Aircraft is being designed for a max reentry AOA of 40 to 50 degrees similar to the space shuttle. Other options, such as slowing the vehicle before it reenters the dense part of the atmosphere have been proposed in the past. These options will be examined to determine whether they have merit for this type of system. However, our intent is to fill in the database for high AOA flight in ongoing ground technology programs, and hopefully increase the X-Aircraft AOA as the flight test program proceeds.

The genesis of the airframe experiment is from a program called HAVE REGION¹ executed in the late 1980's. HAVE REGION fabricated and tested major airframe cross sections of high propellant mass fraction RLV's. The airframe cross sections were then tested using liquid nitrogen in the propellant tanks and quartz lamps on the outside to simulate multiple ascent and orbital reentry mission cycles respectively. Throughout the test, dynamic mechanical loads representative of the ascent and descent environment were imposed on the test structure.

Boeing, Lockheed-Martin, and McDonnell Douglas built and tested airframe cross sections at scales ranging from 40 to 100% of full scale and at costs ranging from \$11 to 15 million. Figure 7 portrays the structure for the Boeing Reusable Aerospace Vehicle during testing. Extrapolating this cost data to a composite airframe structure at the scale of FAST suggests the ground demonstration program can be executed at a total cost of less than \$3,000 per lb of experiment weight. Use of modern composites and design processes can help further reduce costs and deliver an affordable ground experiment.

Subsystems Experiment. The subsystems experiment(s) are not as well defined as the airframe experiment delineated above. Essentially, this experiment is envisioned as one or more coordinated experiments leading to an

“iron bird” demonstration of critical subsystems and operability on the FAST X-Aircraft. To get to that point several elements are envisioned; a Flight Operations Control Center (FOCC) for operations management and control, a limited avionics rack that simulates the X-Aircraft including health management functions, and integrated software such as AGN&C and ISHM (Adaptive Guidance, Navigation & Control and Integrated Systems Health Management). Over time, these experiments can be interconnected within the FOCC and expanded into a full iron bird simulation similar to what is routinely built and tested in aircraft programs.

The FOCC experiment provides the core element in the above architecture, enabling simulation of the CONOPS for both the X-Aircraft and future operational systems. The mission cycle includes rapid mission planning, 3-DOF and 6-DOF pre-flight mission simulations, pre-flight ground operations preparation and support, take-off and flight execution (virtual or actual), then landing and turnaround ground operations. All of the above can notionally be accomplished within a “cockpit-like” environment consisting of no more than three console positions: Flight Manager, Deputy Flight Manager, and Crew Chief.

Once an X-Aircraft flight processor is selected, then the FOCC can be used to provide command, control and health management functions while interfacing with a real or virtual avionics rack. The avionics rack may be little more than the flight processor and X-Aircraft data base that enables simulation of the various technologies and operations to be demonstrated on the X-Aircraft, or it could be a full redundant avionics architecture, albeit probably still missing key elements such as RF equipment. Such an architecture could allow simulation of all the different phases of the mission, and provide a testbed for incorporating AGN&C and ISHM technologies over time.

The AGN&C technology leverages ongoing research programs at AFRL that accomplish real time trajectory recalculations during the flight. Unlike traditional guidance systems that fly on a “wire in the sky,” where the time and position is pre-calculated before flight, an AGN&C system will recalculate the optimal trajectory from any point in the flight through mission completion. Consequently, the aircraft could potentially recover from many failure conditions, including loss of a control surface. Alternatively, many other malfunctions could result in the aircraft not being at the pre-calculated time and spot in the sky, yet the AGN&C would simply execute the next best trajectory required to complete the mission. Perhaps more attractive, the technology lends itself to greatly simplifying mission abort planning. For example, simply designate the abort landing location and the aircraft would find the optimal way to land at that location.

ISHM technology could also be incrementally demonstrated on this program. One of the issues with ISHM technology is that it is potentially all encompassing and could cost a tremendous amount to develop. A working FOCC testbed using a HITL flight processor could potentially begin to incrementally demonstrate how

ISHM algorithms could be implemented on the vehicle. Early algorithms can be implemented and tested in a HITL and SITL environment, then more complex algorithms as the predictive technology matures. This kind of software rapid prototyping approach may be the only affordable way to begin implementing the more complex ISHM architectures envisioned in the labs today.

As the subsystems testbed continues to mature, the vision is to evolve it into a full iron bird demonstration; potentially incorporating actuators, propulsion, gimbal systems, and even the airframe experiment with its structural health management. The model providing a reasonable analogy to how the experiment would ultimately look is the J/IST iron bird technology demonstration used to support the early Joint Strike Fighter program. However, funding limitations and alternative concepts solicited from industry will undoubtedly help refine how the subsystems experiment evolves in the future.

Propulsion Experiment. Two options exist for the FAST X-aircraft propulsion system. In one scenario, the program uses a near off-the-shelf rocket engine. In the second, a small affordable propulsion experiment would demonstrate critical propulsion technologies and the potential for low cost development. Because the FAST experiment is primarily a demonstration of critical airframe technologies, either scenario can provide a legitimate solution for the X-Aircraft needs, albeit there may be significant differences in cost, schedule, performance and risk.

As mentioned earlier, the X-Aircraft is sized around four CHASE 10 engines, 5 PWR RL-10's or a single SpaceX Merlin engine. The first two engines utilize LOx/LCH₄ as the propellant system while the third possibility utilizes LOx/RP. All of these engines have a regeneratively cooled chamber and nozzle. These engines are either commercially available or could be developed reasonably rapidly and at a reasonably low cost. For a commonly sized vehicle, the first two engines are small enough to support the multi-engine, engine-out requirement in Table 1. The Merlin engine has a thrust level which allows the use of a single engine which will decrease the required engine maintenance between flights; however, it obviously would not support engine-out.

The CHASE 10 and SpaceX engines are commercially developed, and both are scheduled to undergo final prototyping and testing during 2007. The RL-10 is an existing Pratt & Whitney Rocketdyne engine that requires significant modifications, but could be developed and prepared for X-Aircraft flight within 2 to 3 years. All of the engines require modification and test to specific requirements levied by the X-Aircraft. In particular, a throttle depth requirement between 40 and 60% helps enable an incremental flight envelope expansion program. For example, the X-Aircraft can take off on two engines with a partial propellant load and fly subsonically once around, then land near the take-off site. Conversely, the X-Aircraft could fly with a maximum propellant load and land downrange, achieving a velocity of approximately Mach 7.

In addition to off the shelf propulsion options, AFRL has been carrying a number of potentially clean sheet engine concepts. Companies such as XCOR, D&E Propulsion, Aerojet and different companies proposing use of Russian engine technology have identified LOX/Methane propulsion options. With the exception of the modified Russian engines, most of these rockets are essentially clean sheet designs of an engine. Costs are controlled by limiting the thrust to approximately 20,000 lbf sea level, and designing to a limited cost bogey by limiting the performance Isp, T/W, etc.). Such solutions are perfectly acceptable for an X-Aircraft but are suboptimal for future operational systems. Nonetheless, they can potentially demonstrate at very reasonable costs a number of next generation propulsion technologies critical to future RLV concepts.

Comparing LOX/Methane to LOX/RP has been a subject of many studies with seemingly contradictory results. In all of these studies, Methane and Kerosene are very closely matched. In fact, the difference is likely within the uncertainty of the studies being performed. AFRL has a separate program – Hydrocarbon Boost Technology Demonstrator – which seeks to provide analysis, design, fabrication, and delivery of critical LOX/RP components for a demonstrator engine. Aerojet Corp was awarded \$110 million for the Hydrocarbon Boost program to mature a near full scale, highly operable and reusable LOX/RP Ox-rich staged combustion cycle engine. When the Hydrocarbon Boost program matures it will provide a superior first stage booster option. The Hydrocarbon Boost program is described in more detail in other papers.

The interest in LOX/Methane for FAST is partially to provide more data for the comparison of propellants given the LOX/RP focused Hydrocarbon Boost program. But also, several factors including the potential for higher specific impulse, the potential for improved operability features at the system level, and the lack of any LOX/RP engines in the size class of interest (except the Merlin which is a single engine configuration) provide intriguing potential benefits for an operational vision vehicle using a re-usable upper-stage. Figure 8 reviews some of the other possible advantages of LOX/Methane including autogenous pressurization of the main fuel tank; applicability to RCS, orbital maneuver and auxiliary power systems; reduced coking; facilitation of a minimum weight common bulkhead tank due to the minimal temperature differential between the propellants; and minimal purge requirements for turnaround operations due to the rapid boil off characteristics of the propellants. Any single advantage of the LOX/Methane system is marginal compared to LOX/RP. Indeed, LOX/RP systems are slightly smaller than LOX/Methane due to propellant bulk density effects; however, at the system level LOX/Methane could provide a significant operability advantage. Certainly enough of an advantage to justify including a LOX/Methane propulsion experiment on the X-Aircraft. Together, a LOX/RP booster and a LOX/Methane upper-stage vehicle could provide first rate propulsion options for next generation spacelift needs.

OPERABILITY GOALS

Table I contains a number of operability goals which the FAST program has taken to heart. The thresholds and goals presented, if successfully demonstrated in the X-Aircraft, would go a long way towards validating the vision of aircraft-like access to space. The thresholds represent reasonably aggressive but achievable values based on prior RLV studies. The goal values are a reasonably conservative assessment of the opportunity potential based on aircraft operability today. A brief discussion of the key goals in Table I will help highlight the importance of an operable design and test program for FAST including turnaround, engine out reliability, crew size and recurring operations cost.

Responsiveness/Turnaround. Responsiveness is the time required to launch an aircraft that has been pre-processed and placed on in a mission ready condition. There are many challenges related to achieving the turn-time on launch vehicles that differ from aircraft. Examples include differences in heat-soak back temperatures, changes in the amount of propellant, the need to change orientation from horizontal to vertical, and stage integration issues that are not usually present in aircraft. The threshold and goal values for FAST range from 120 to 30 minutes. By both ELV (think ICBM) and airplane standards these values are achievable. Turnaround is the time from wheels on ground to take-off with threshold and goal values of 48 hrs and 4 hrs. Because space systems only have the space shuttle as an example even the 48 hr turnaround time appears very aggressive. The goal value appears impossible unless you consider that many large and complex aircraft today, much larger than the FAST X-Aircraft, routinely accomplish equivalent turnaround operations.

Figure 9 is a technical assessment of the potential to design a RLV for rapid turnaround. The first bar in the graph is the serial processing time for the Delta ELV booster. Each subsequent bar highlights the potential reduction in processing time by incorporating specific processes, technologies, or system approaches. As shown in the figure, even using ELV data the potential exists to push turnaround time below 48 hrs. Because of the often emotional uncertainty in how “aircraft-like” an RLV can be, an X-Aircraft is ultimately essential to understand how far turnaround operations can be pushed. When it comes to operability claims like turnaround, no one is going to believe paper studies or even ground demonstrations – flying hardware is essential. Similarly, designing for rapid turn is a critical issue that drives operability and recurring cost more than any other design feature.

Engine Out Reliability. The reliability of multi-engine aircraft is significantly better than single engine aircraft based on almost a century of experience. However, when aircraft engines fail, they usually fail in a benign manner; they don’t typically fail catastrophically. Conversely, few rockets have been designed for reusability and little data exists on how and whether they can be designed for benign failure. One data point is the expander cycle, which historically fails

almost exclusively in a benign manner. Alternatively and theoretically, an engine health management system can predict upcoming failures and shut down the engine before a catastrophic failure occurs. Over the history of ELV launches a large percentage of launch failures were due to an engine failure. Consequently, there is a potential huge advantage to developing engines where the probability of benign failure is much greater than catastrophic failure.

Figure 11 highlights that an engine out capability greatly improves the probability of always recovering the aircraft, provided the probability of benign failure is much greater than that of catastrophic failure. Indeed, as illustrated in the figure even a couple of order of magnitude difference pushes the probability of losing an aircraft into the range of some military aircraft. To both take advantage of, and begin exploring the potential for dramatically better aircraft reliability, the FAST program established a requirement for an engine out capability from liftoff; an all altitude mission abort capability. Taking advantage of that potential and demonstrating improved aircraft reliability will require a prudent design, or incorporation of design features like reliable engine cycles, health management, design margins (especially in the turbomachinery), thorough testing, and simply designing for reusability and reliability. With careful design, the X-Aircraft and its propulsion system will begin exploring the path to aircraft reliabilities for space access.

Crew Size. Much has been said about the need to develop launch systems that do not require a “standing army” to process and fly. Both ELV and aircraft experience offers an abundance of example vehicles that small ground crews can operate and fly, albeit there are many more aircraft examples. Figure 10 highlights the historical aircraft maintenance man-hour trend data for different size aircraft. Both this data and experience from early medium lift ELV’s supports the threshold and goal crew size range in Table I; namely, 15 to 6 people respectively. Essentially this is the total “on-aircraft” crew size supporting both ground and flight operations. As with turnaround, crew size is a key parameter that will drive many other features of the design and is synergistic with rapid turnaround. A system that is designed for rapid turnaround will likely have a minimal crew size and vice versa. Only the act of flying hardware can validate the credibility of small crew sizes.

Operations Cost. Early consideration of recurring operations cost is paramount to smart future acquisitions. Ultimately turnaround time and crew size drive the need for reliable component and subsystem designs, all of which drive the resulting flight system recurring operations costs. Although we removed the axis values on Figure 12 to avoid contentious discussions, the figure highlights several key issues associated with RLV’s. Foremost, if the flight rate is very low the recurring cost will be very high. Even in the airplane world a wing of aircraft that only flies a few times a year has an unreasonably high recurring flight cost. More than one Air Force aircraft has left the inventory for that very reason. The space shuttle’s low flight rate and high recurring cost also illustrates this point.

Conversely, higher flight rates can exponentially reduce the recurring flight operations cost to the point where fundamentally new missions and CONOPS become possible.

The second issue highlighted in the figure is that designing for operability has a significant impact on recurring costs. For example, the model assumes use of F-15 O&S parameters in one case and C-5 parameters in the other. Use of parameters from the F-15, a system designed to fly frequently during crisis, yields significantly lower recurring operations costs. Although it is recognized that part of this cost difference is the difference in size and mission of these two aircraft, it does identify that designing for the –ilities (Reliability, Maintainability, Supportability, Availability, etc.) will go far toward minimizing recurring costs.

To establish credible (and aggressive) goals for the X-Aircraft recurring ops cost, the O&S cost model for the F-15 and C-5 was reviewed. The recurring flight cost of both aircraft was roughly 2.7X greater than the cost of fuel, consumables, and spares, including Class IV mods. Although the analogy is not perfect, the threshold and goal values for the X-Aircraft were respectively set at 3X and 6X the cost of propellants, consumables and spares. Demonstration in this range would certainly demonstrate the potential for aircraft operability and affordability.

Defense Systems Management College teaches that 70% of life cycle costs including recurring operations costs are set in concrete during the design phase of any program, before any hardware is built. The corollary to this lesson is that operability doesn't cost much if it's designed in from the beginning, but it can be very expensive if the program ends up retrofitting the system for operability. The FAST program is taking these lessons to heart and designing the X-Aircraft to both demonstrate the critical reusable technologies and the associated operations required to validate aircraft like operations.

SPACE ACCESS FUTURE APPLICATIONS

An experimental aircraft is an essential stepping stone to future operational systems. We must learn how to build these new classes of RLV, as well as how to operate them. The FAST ground and flight experiments will demonstrate many of the technologies and operations associated with non-crewed reusable 1st and 2nd stages. These technologies can be applied to a wide range of possible future spacelift and aircraft systems. In particular, the technology will directly support reusable boosters that augment performance on today's ELV's. A variant is the Hybrid RLV/ELV in which the reusable booster deploys a small payload to orbit using an expendable upper stage. Although both of these options have the potential to enhance and/or provide significant capability they are also dependent on a mission model with a sufficient satellite flight rate to justify the use of a reusable booster.

The application which has the potential to both reduce operating cost and enhance reliability by another order of magnitude is the fully reusable vehicle including the 2nd stage. A reusable 2nd stage with aircraft like operability has the potential to enable a wide range of future sortie missions. Sortie missions may only fly for a few hours, but they can accomplish many military missions and be far more survivable than satellites locked into precisely predictable orbits. Sortie aircraft will never replace satellites, but in the rapidly approaching future where many nations can threaten US space assets, a sortie capability may be the only credible way to maintain critical space capabilities. Satellites can always be taken out once they are located precisely, but locating a sortie aircraft will take many hours or even days – it is inherently survivable simply because it returns to base and prepares for the next mission before anyone can find it precisely.

Another dramatic example of the benefit of sortie missions comes from the SR-71. The SR-71 flew synthetic aperture radar missions more than a decade before they were flown in space. The ability to responsively launch, fix, and launch again can drastically increase the pace at which space technology is developed, tested, and employed. The sortie mission also offers other unique capabilities including first pass overflight of reconnaissance targets, offset sequential passes for side looking sensors, or even specialized orbits with as many as six passes over a theater within 24 hours. Other applications of these capabilities are also possible; however, all these missions only make sense if highly operable aircraft like flight is possible.

There is also significant synergy between the X-Aircraft technologies and operations being developed by FAST and the needs of the emerging entrepreneurial space access sector. For example, rapid turnaround, reliability, small crew sizes, low ops cost and all the other –ilities will be essential to establishing viable private sector space access. Today, FAST is focused on the more challenging and higher speed technologies associated with flight from ground to orbit and back, while the private sector is focused primarily on the suborbital tourism market flying in the Mach 3+ range. However, within the decade several Mach 3 privately developed aircraft will be flying and with luck making money. Many of those entrepreneurs will look to FAST to help mature the technologies and operations associated with flight to space and back.

The Air Force is eager to help the emerging private sector establish a robust space access industry. Borrowing from Alfred T. Mahan's maritime power theories of a century ago, the most credible path to space power will be built on a robust commercial space access industry. The military-entrepreneurial synergy may well provide the path to robust and affordable space access capabilities in the 21st century, and provide a stepping stone to fundamentally new space capabilities and incredible wealth on the space frontier.

SUMMARY

Successful development of the FAST ground experiments and follow on X-Aircraft will bring many benefits. Its small size and focused technical objectives make it affordable and timely. The program is structured to accomplish the ground experiments through 2011, and then transition to either an integrated ground demonstration of an X-Aircraft or a flight demonstration program. These experiments will provide a real and substantial step towards affordable and responsive access to space. It will demonstrate high-tempo operations while using launch and recovery methods, technologies, and subsystems that could be used on many different future operational aircraft concepts. In addition, it will provide an ongoing flight test capability for future technologies, operations, and systems being considered for emerging spaceplane and hypersonic test aircraft. Its success would prove that future RLV's are technically and operationally feasible and can fulfill the promise of substantially lower operating costs, higher reliability, and more frequent flights – "Aircraft-Like" Operations. None of the above will be easy nor do we have an abundance of funds to throw at the problem; however, as our boss Gen Bruce Carlson recently told DARPA, "we are in this for the long haul!"

REFERENCES

- 1. Have Region Program, Major Stephen Clift, September 1989 Briefing Charts**

Figure 1 FAST Vision...



Figure 2 Technology Feeds Future Flight Systems

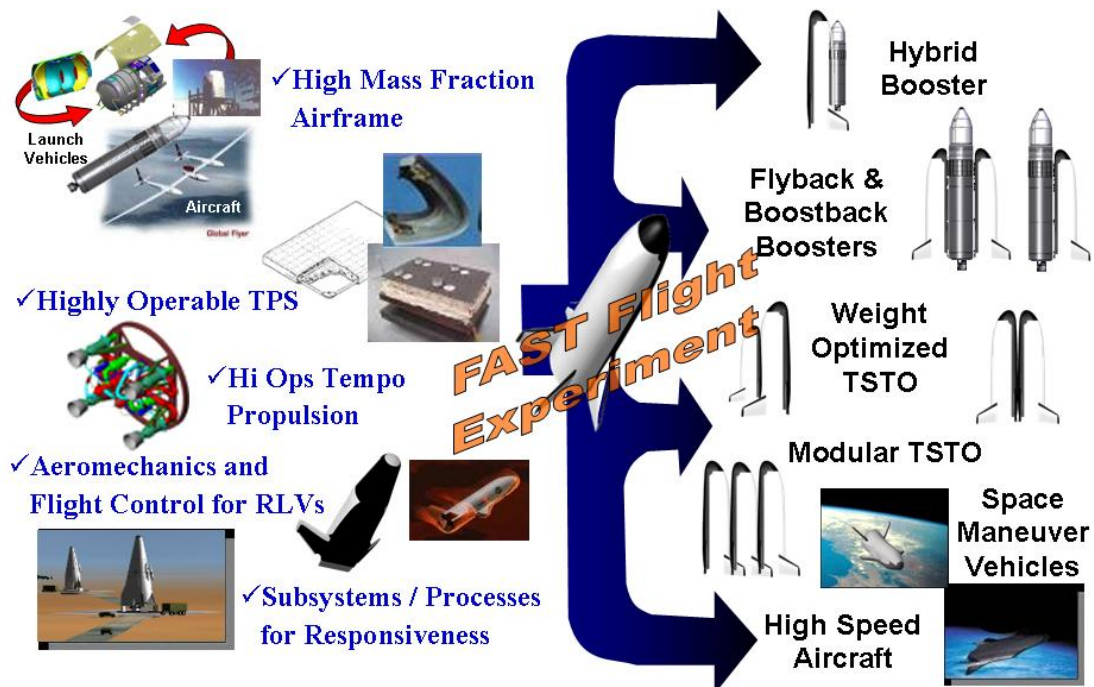


Figure 3 FAST X-Aircraft Size and Weight

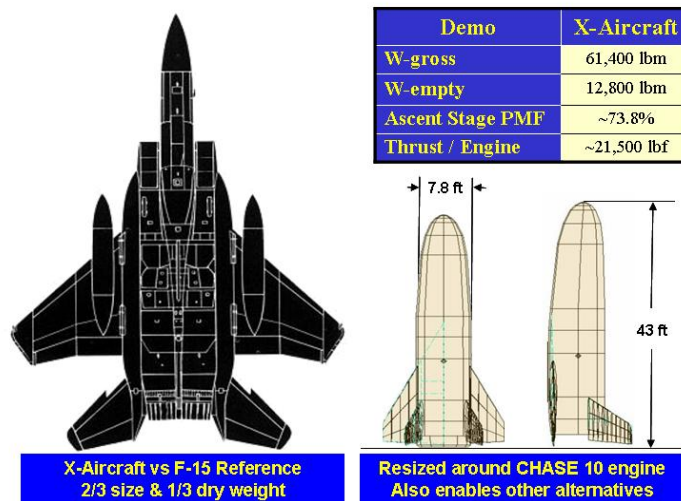


Figure 4 Technology is Scaleable to Future Flight Systems

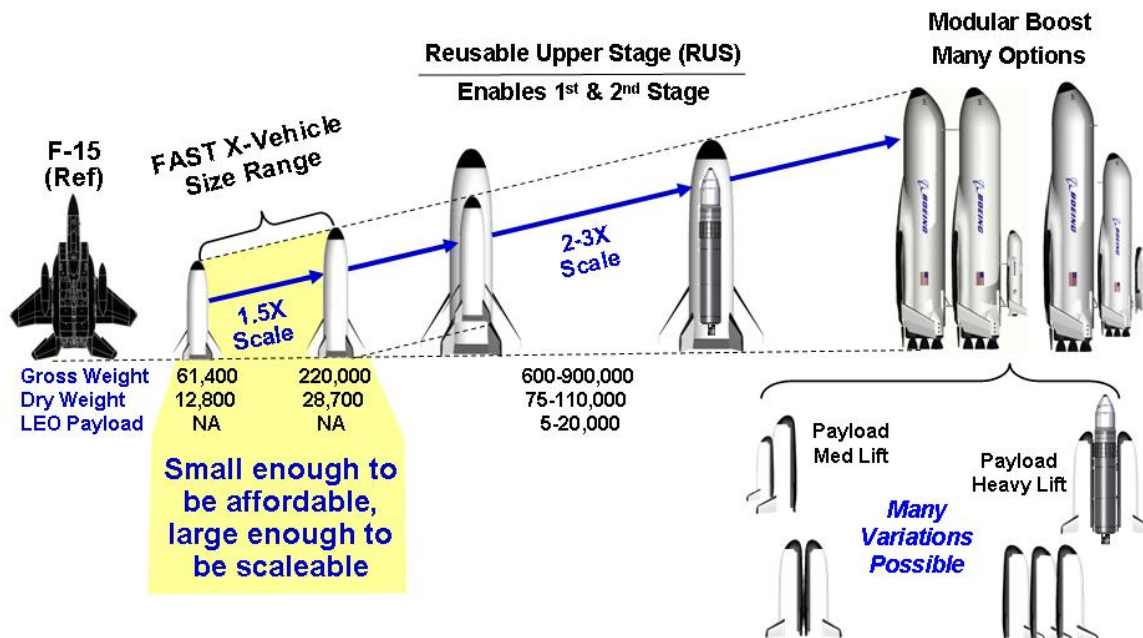


Figure 5 Program Schedule

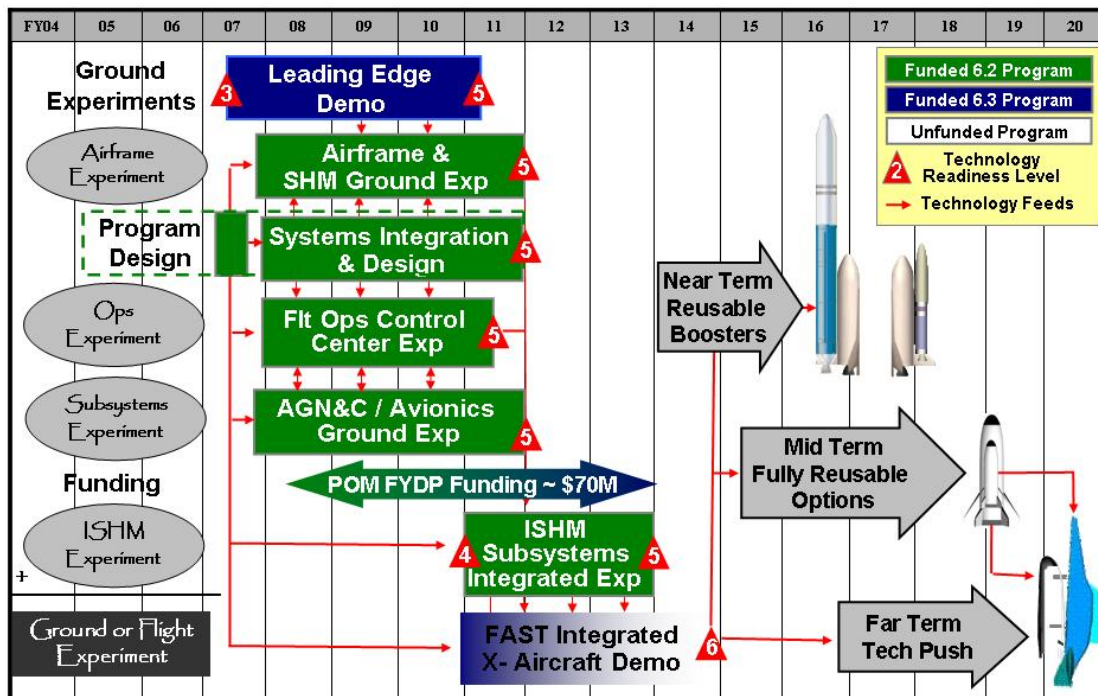


Figure 6 Incremental Stepping Stone Program

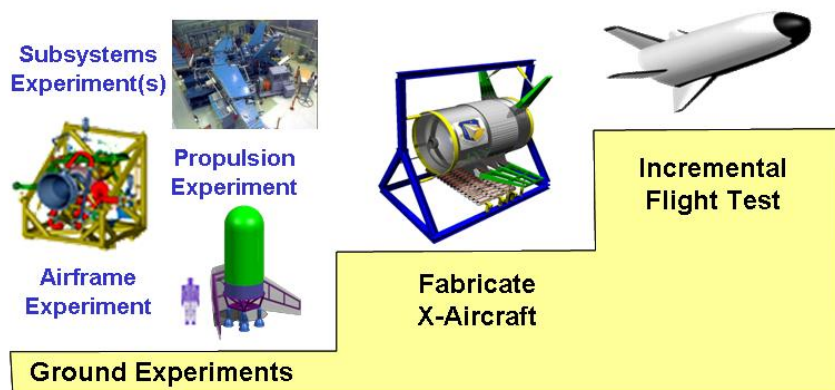


Figure 7 Boeing HAVE REGION RLV Structural Test



Figure 8 LOX/Methane Potential Advantages

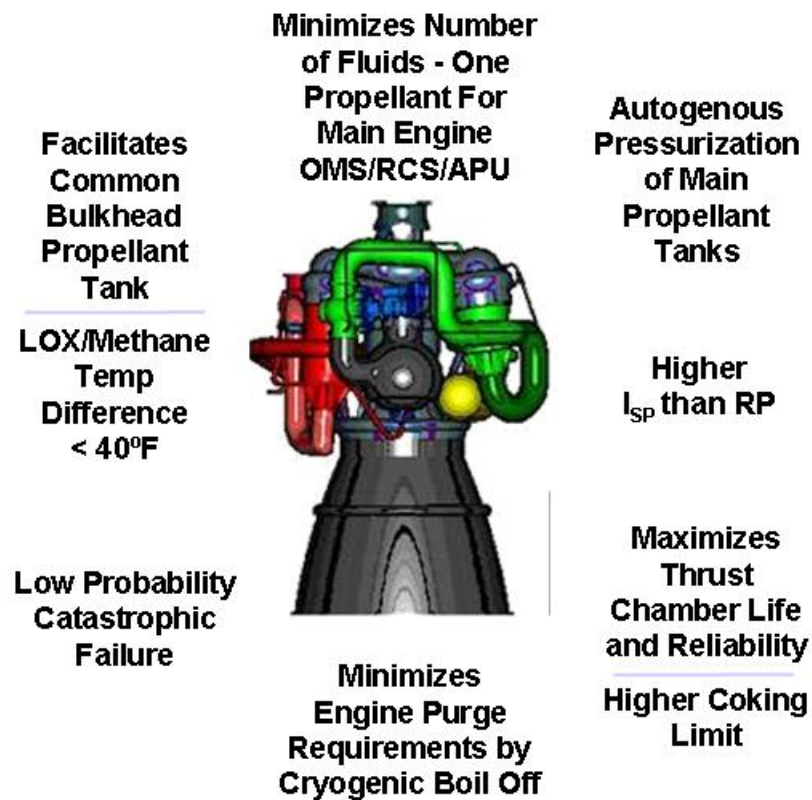


Figure 9 Potential for Rapid Turnaround

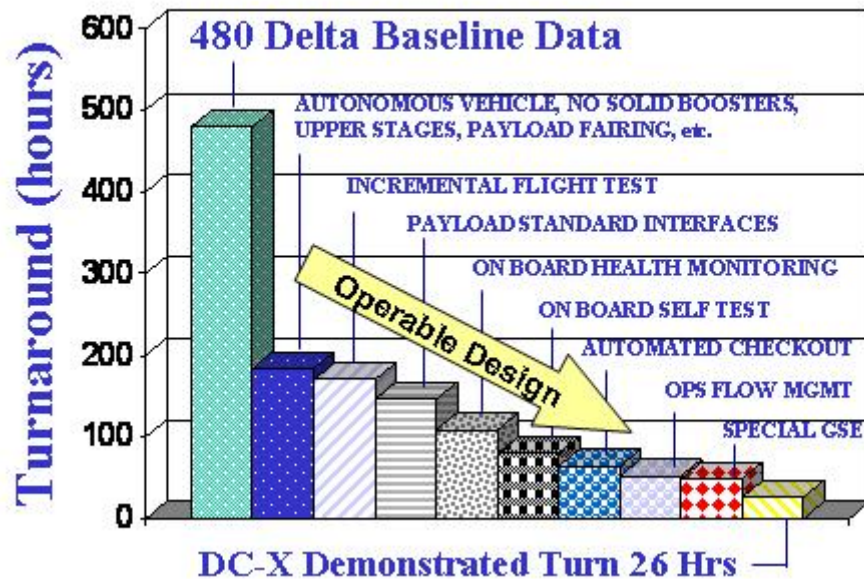


Figure 10 Historical Aircraft Data Supports Small X-Aircraft Crew Size

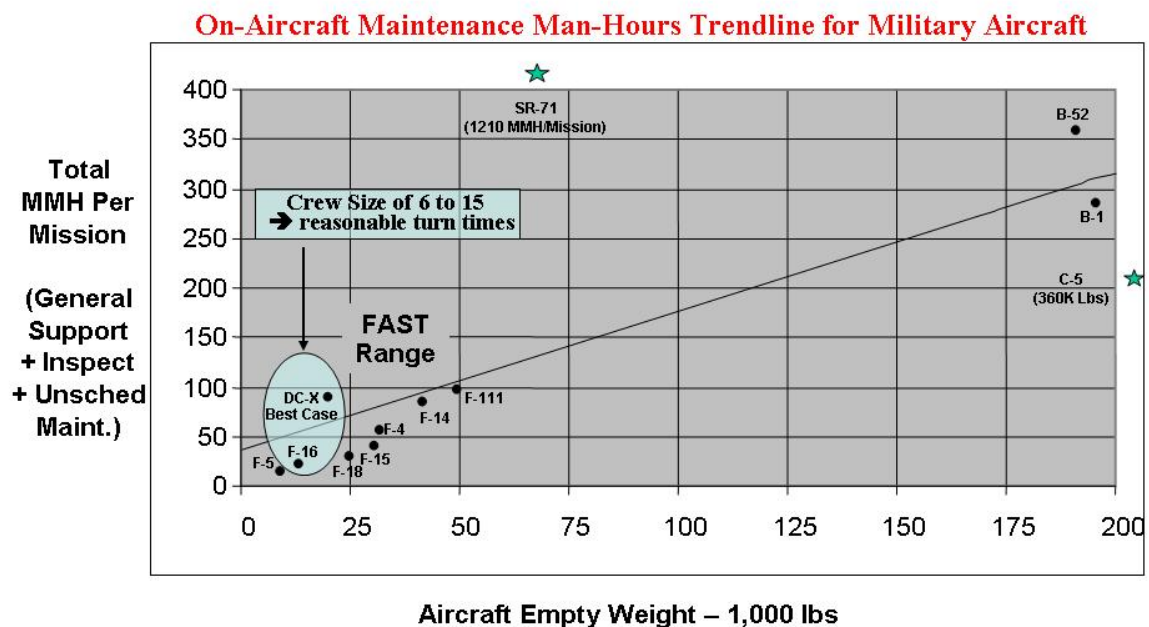


Figure 11 Engine-Out Can Increase Aircraft Reliability

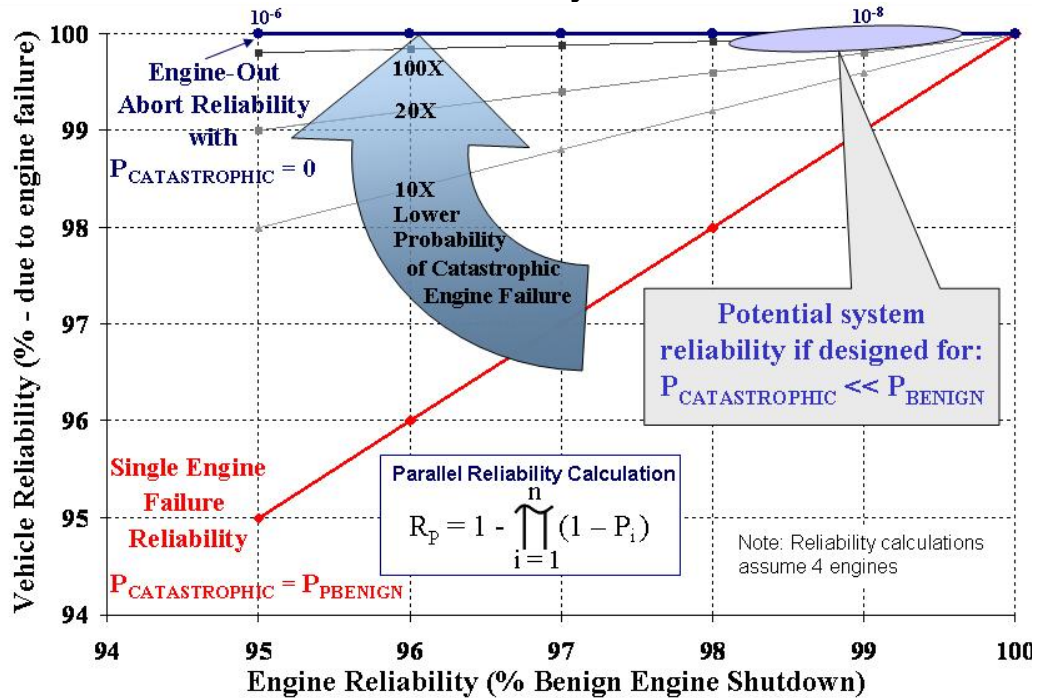


Figure 12 Recurring Ops Cost Driven by Design and Flight Rate

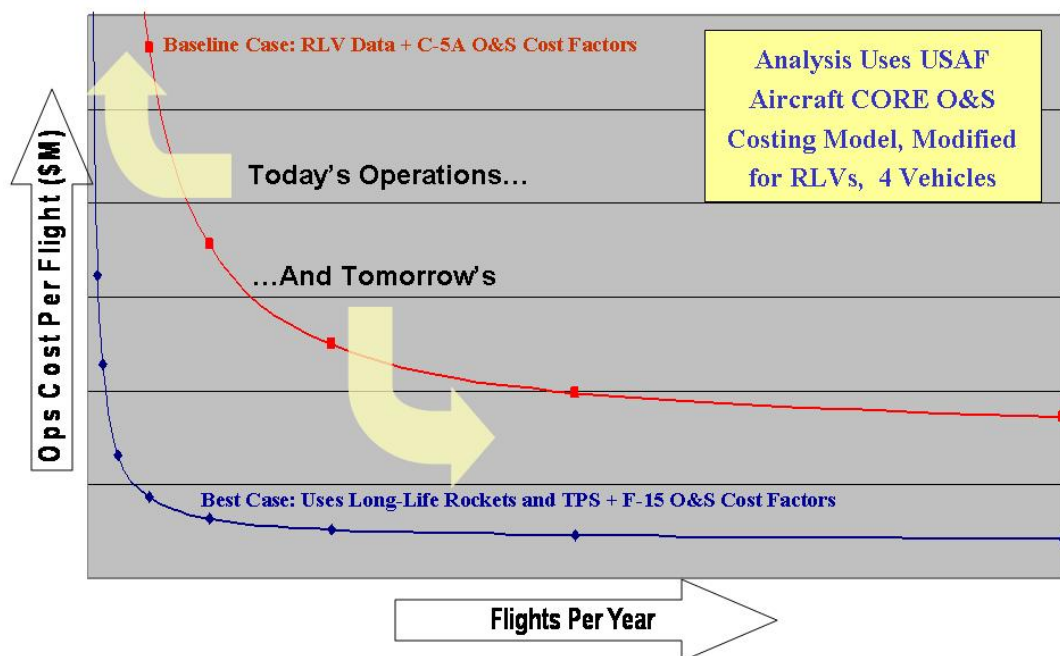


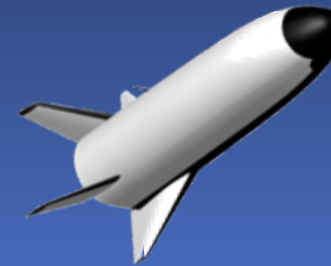
Table I Key Program Goals & Thresholds

Measures of Merit	Threshold	Goal
Maximum Hypersonic L/D	No Requirement	Sufficient for once around from polar orbit.
Take-off and Landing Mode	Demonstrate Vertical Take-off / Horizontal Landing	Demonstrate Vertical Take-off / Horizontal Landing and technology for Vertical Take-off / Vertical Landing
Controlled “High Alpha” Flight	Demonstrate controlled flight at an angle of attack greater than 40 degrees	Demonstrate controlled flight at an angle of attack greater than 70 degrees
Single-Stage Vehicle Performance	Demonstrate powered flight to at least 4,000 ft/s and 100,000 ft, simultaneously	Demonstrate powered flight to at least 7,000 ft/s and 180,000 ft, simultaneously
First-Stage, Rocket-back Trajectory Performance	Demonstrate in-flight critical events for a first-stage, rocket-back trajectory. Critical in-flight events include vehicle pitch over, main engine throttling and/or main engine shut-down & restart, and maneuver to a gliding re-entry orientation.	Demonstrate full return-to-launch site, rocket-back trajectory to and from a reference staging point. The reference staging point is at least 5,500 ft/s, at least 140,000 ft, and a flight path angle of at most 30 degrees.
Engine-out Performance	Demonstrate safe abort (i.e., recovery of the main demonstrator vehicle) with one engine-out from liftoff.	Demonstrate 85% of threshold single vehicle performance with one engine out from liftoff. [Powered flight to at least 3,400 ft/s and 85,000 ft, simultaneously]
Two-Stage Vehicle Performance	Demonstrate in-flight critical events for a TSTO RLV. Critical in-flight events include mated ascent flight and serial-burn or parallel-burn separation. Serial burn separation is empowered staging w/ upper-stage engine ignition. Parallel-burn separation is staging w/ upper-stage engine under power.	Demonstrate in-flight critical events for a TSTO RLV, plus cross-feed of propellants between powered vehicles and powered flight of the second-stage to 5,500 ft/s.
Second-Stage Performance	Demonstrate powered flight to Mach 12 [using steep reentry glide can emulate orbital reentry heat flux and temperatures].	Demonstrate powered flight to Mach 20 [also emulates reentry heat load and full chemistry effects].
Operability (Turn-around Time)	Demonstrate lift-off of a single vehicle within 48 hours following a flight of that vehicle to Mach 4	Demonstrate lift-off of a single vehicle within 4 hours following a flight of that vehicle to Mach 4
Operability (Call-up Time)	Demonstrate lift-off of a single vehicle, from a stored, mission-ready condition, within 120 minutes	Demonstrate lift-off of a single vehicle, from a stored, mission-ready condition, within 30 minutes
Operability (Response Time from Alert Hold)	Demonstrate lift-off of a single vehicle from an unfueled, pad-mounted condition within 60 minutes	Demonstrate lift-off of a single vehicle from an fueled, pad-mounted condition within 15 minutes
Operability (Crew Size)	Conduct all on-aircraft/on-console flight, ground, and maintenance activities with a crew size of 15 or less	Conduct all on-aircraft/on-console flight, ground, and maintenance activities with a crew size of 6 or less
Operations & Maintenance Cost	6X cost of propellant, consumables and spares	3X cost of propellant, consumables and spares

Fully Reusable Access to Space Technology (FAST)



U.S. AIR FORCE



Program

9 April 2007

Jess Sponable, Program Manager
Dr. Jeff Zweber, Chief Engineer
Lt Cole Doupe, Deputy PM
AFRL/VA, Wright Patterson AFB OH

Dr. Rich Cohn, Propulsion IPT Lead
AFRL/PRS, Edwards AFB CA

Integrity - Service - Excellence

DISTRIBUTION STATEMENT A

Approved for public release; distribution unlimited. AFRL-WS 07-0586

➤ **Why FAST?**

➤ **What is Fast?**

➤ **Way Ahead**

➤ **Summary**

Key Objectives



VISION

A 21st century of routine, reliable and affordable flight of diverse fully reusable space access vehicles

Enable Aircraft-Like Space Access Capabilities



Traceable
Scaleable



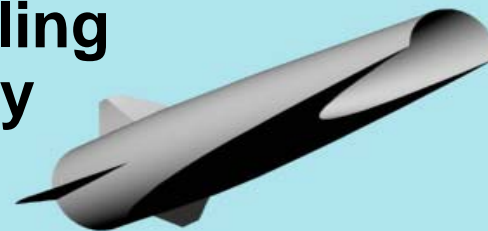
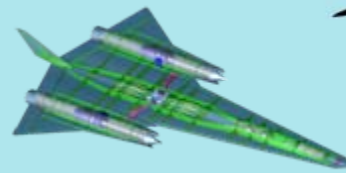
Emerging Industry!

DOD Primes!

Build Healthy Space Access Industry



Spinoff Enabling Technology



to
Air & Space
Sectors

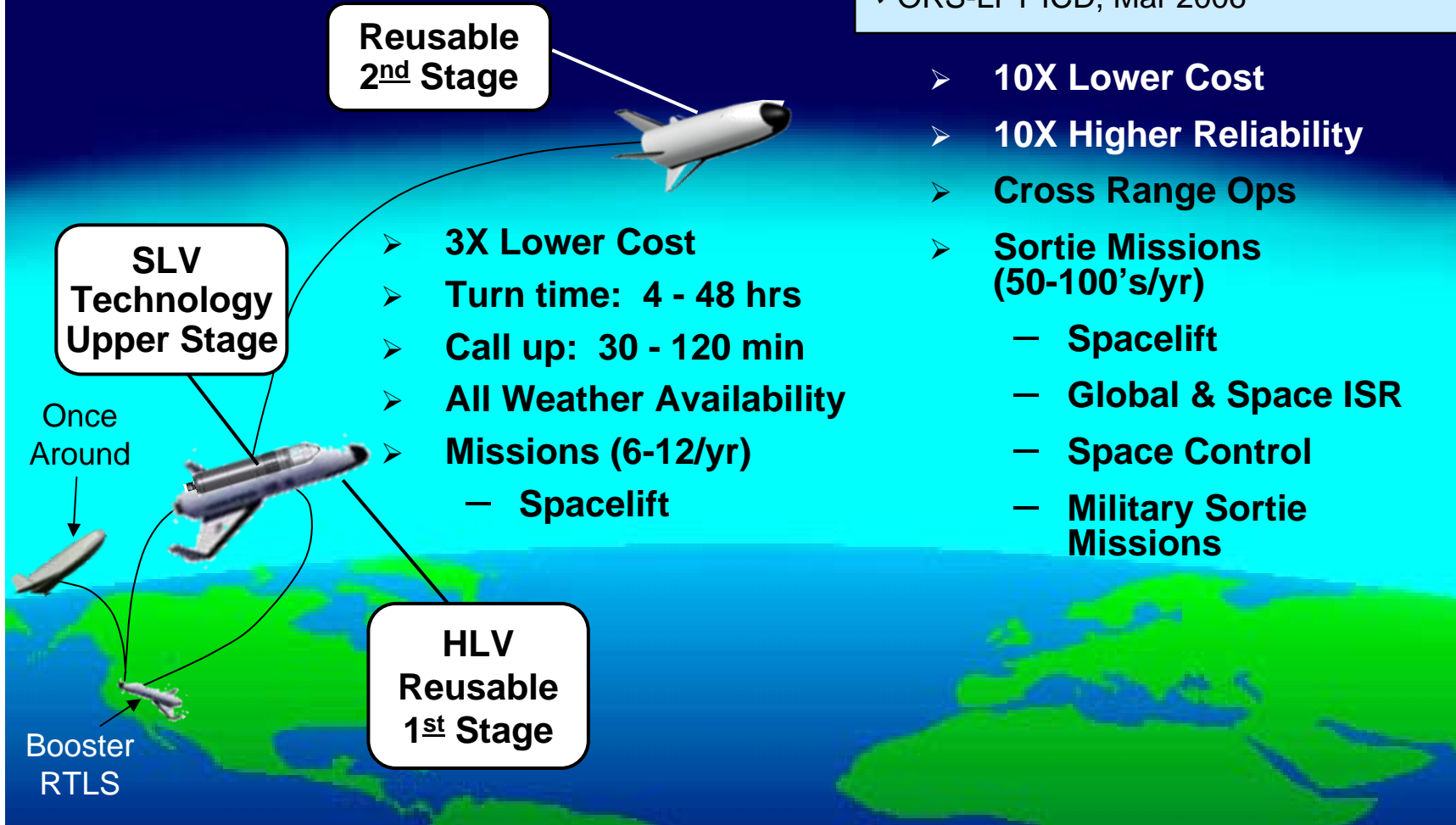


Why FAST?

- *Fully Reusable Access to Space Technology* -



✓ORS-LFT ICD, Mar 2006



Fully Reusable Space Access Operational Vision

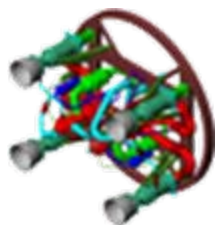
FAST Flight Experiment

- *Technology for Multiple Future Flight Systems* -



✓ High Mass Fraction Airframe

✓ Highly Operable TPS



✓ Hi Ops Tempo Propulsion

✓ Aeromechanics and Flight Control for RLVs



✓ Subsystems / Processes for Responsiveness



FAST Flight Experiment



Hybrid Booster

Flyback & Boostback Boosters



Weight Optimized TSTO



Modular TSTO



Space Maneuver Vehicles

High Speed Aircraft



➤ **Why FAST?**

➤ **What is Fast?**

➤ **Way Ahead**

➤ **Summary**

What is FAST?

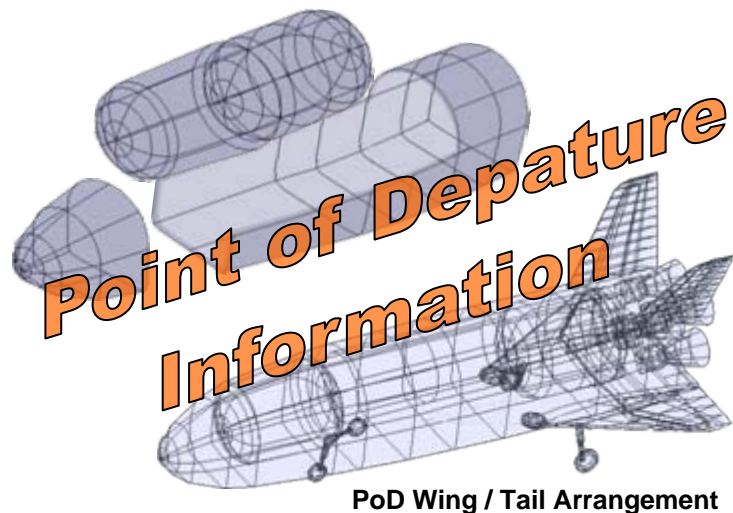
- Built Upon Small and Affordable Experiments -



Point of Departure (PoD) Design

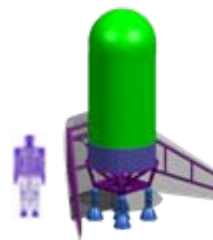
Propulsion	4 Chase-10s
Length	~ 45 ft
GLOW	~ 60K lbm
Dry Weight	~ 16K lbm
Stage PMF Goal	~ 73%

PoD Fuselage Structural Concept



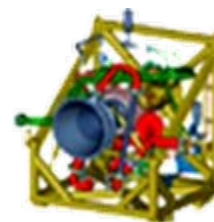
PoD Wing / Tail Arrangement

➤ Step 1 – Ground experiments



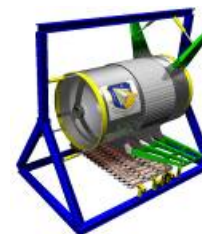
Airframe Experiment

Propulsion Options

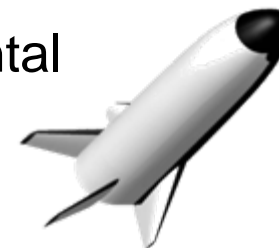


Subsystems Experiment(s)

➤ Step 2 – Fabricate X-Vehicle



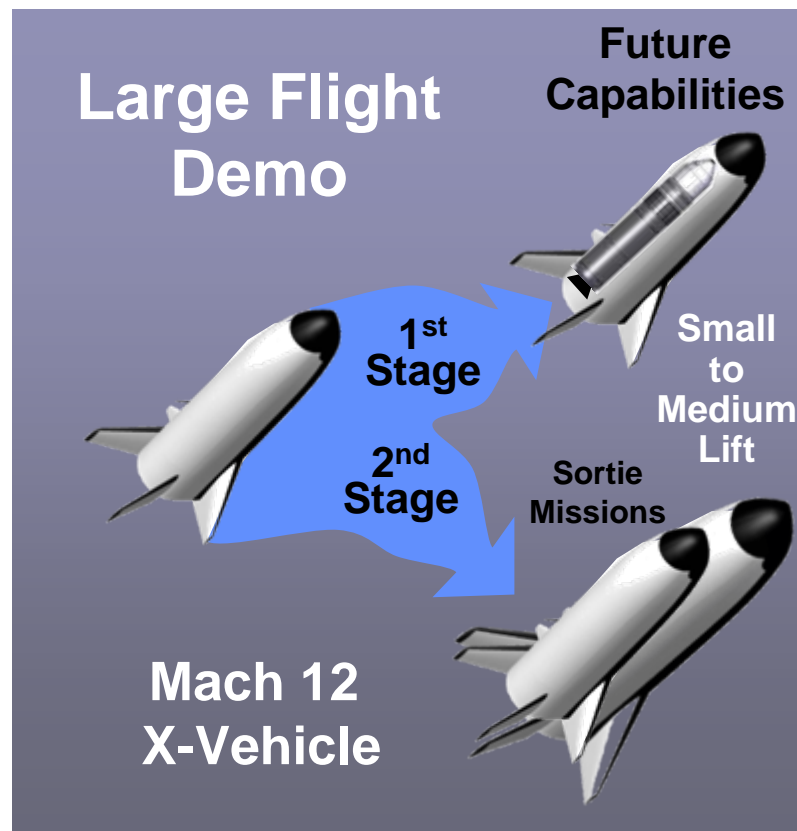
➤ Step 3 – Incremental flight test



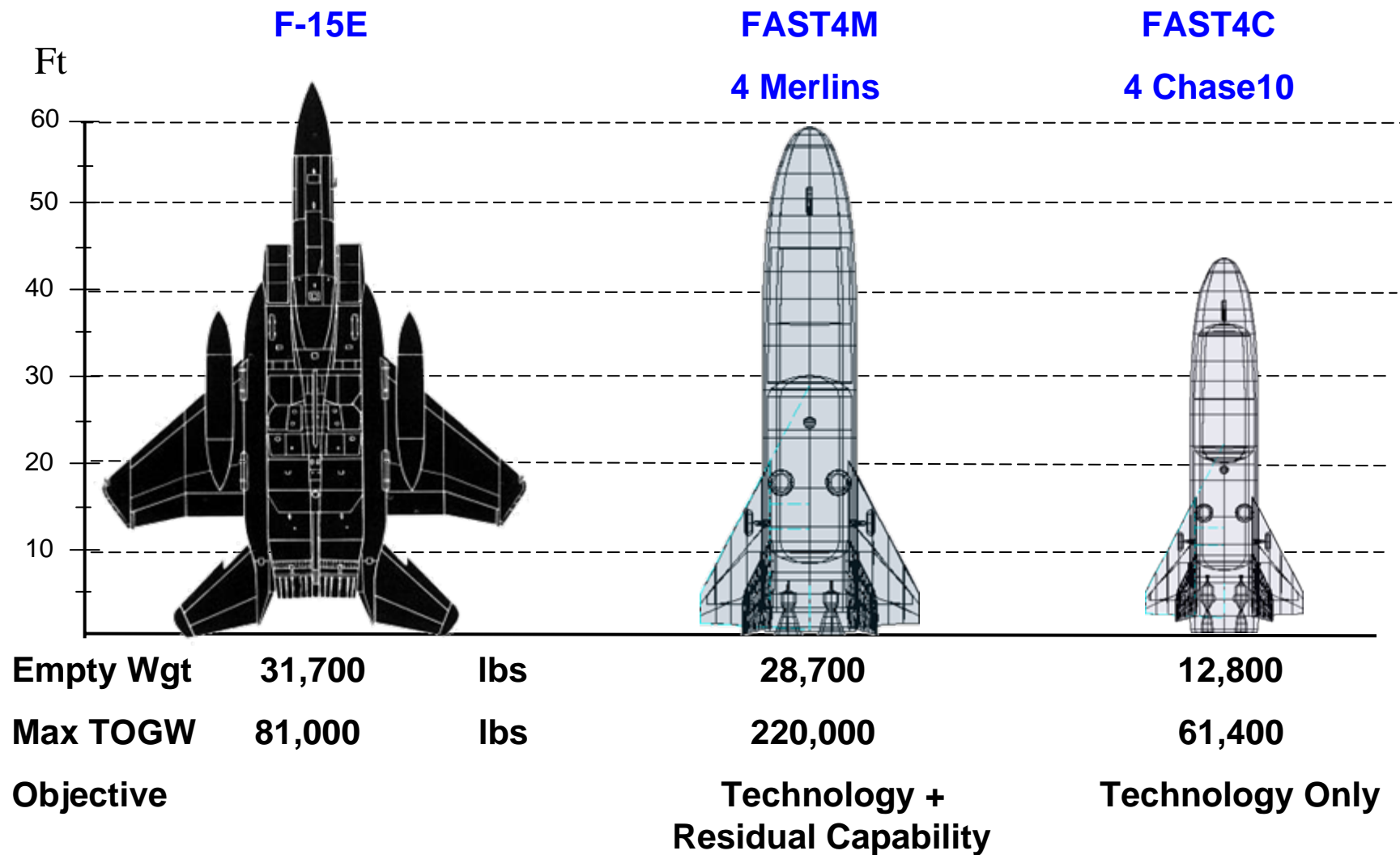
Potential Larger X-Aircraft



- **Ongoing studies based on FAST baseline design**
 - NASA Ames partnered for aerothermal and TPS
 - Reusable Merlin engine option by SpaceX
 - Conceptual Research Corp design
- **Key impacts**
 - Larger vehicle
 - Sized around 4 Merlin engines
 - Potential residual capability
 - Higher risk
 - Higher cost
- **Issue: Are we ready to build large vehicle?**

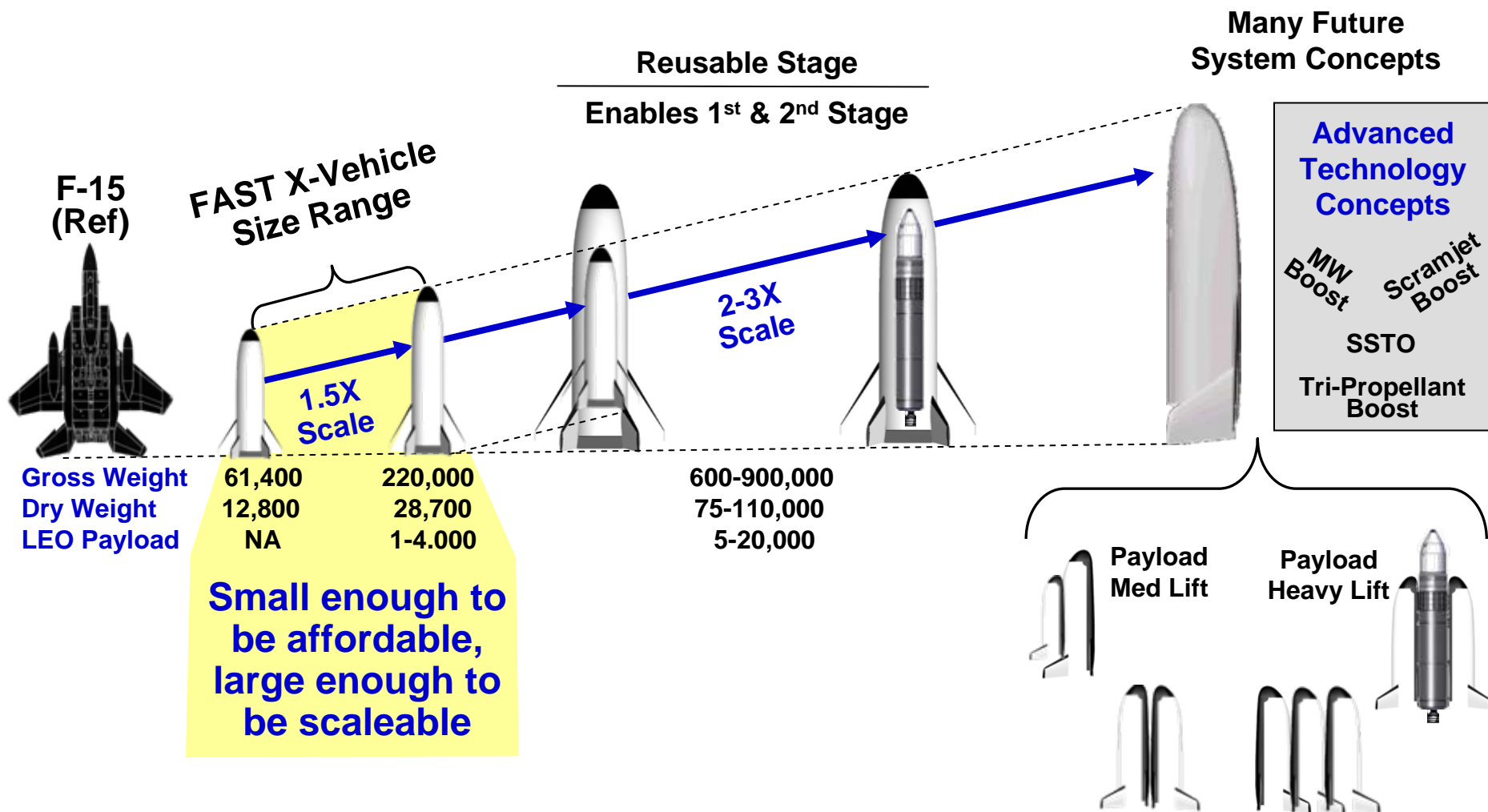


FAST-2 Demonstrator Size Comparison – Current Status



Key Goal

- Scaleable to Future Capability -



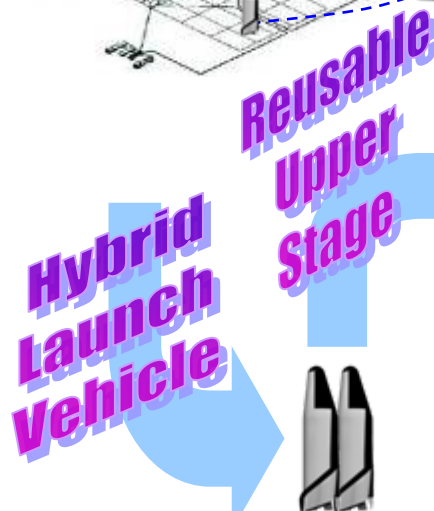
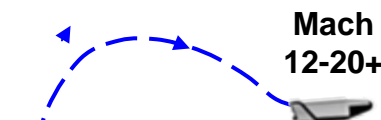
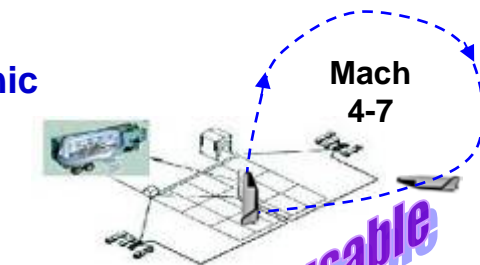
- Design Experiments to Transition to Flight Test -

① Stand Alone Envelope Expansion

- Subsonic to transonic
- Transonic to hypersonic
- Systems Validation
- Aircraft-Like Ops

③ Reentry Skip Glide

- Reentry Environment
- Full chemistry thermodynamics



Minotaur IV/Falcon IX Option

- Stage connection loads & ground ops
- Test staging dynamics & operations
- Test reentry heat rate/temp
- NOT a test of bimese concept

② Modular Staging

Key Ops Measures of Merit		
	Goal	Threshold
O&M Crew	6	15
Call Up - min	15	120
Turn time - hrs	4	48
O&M cost vs fuel, spares & consumables	3X	6X
Engine Out	---	Safe Abort

**Incremental Flight Test Program (unfunded)
Or
Ground Test of Integrated Structure/Subsystems (funded)**

➤ **Why FAST?**

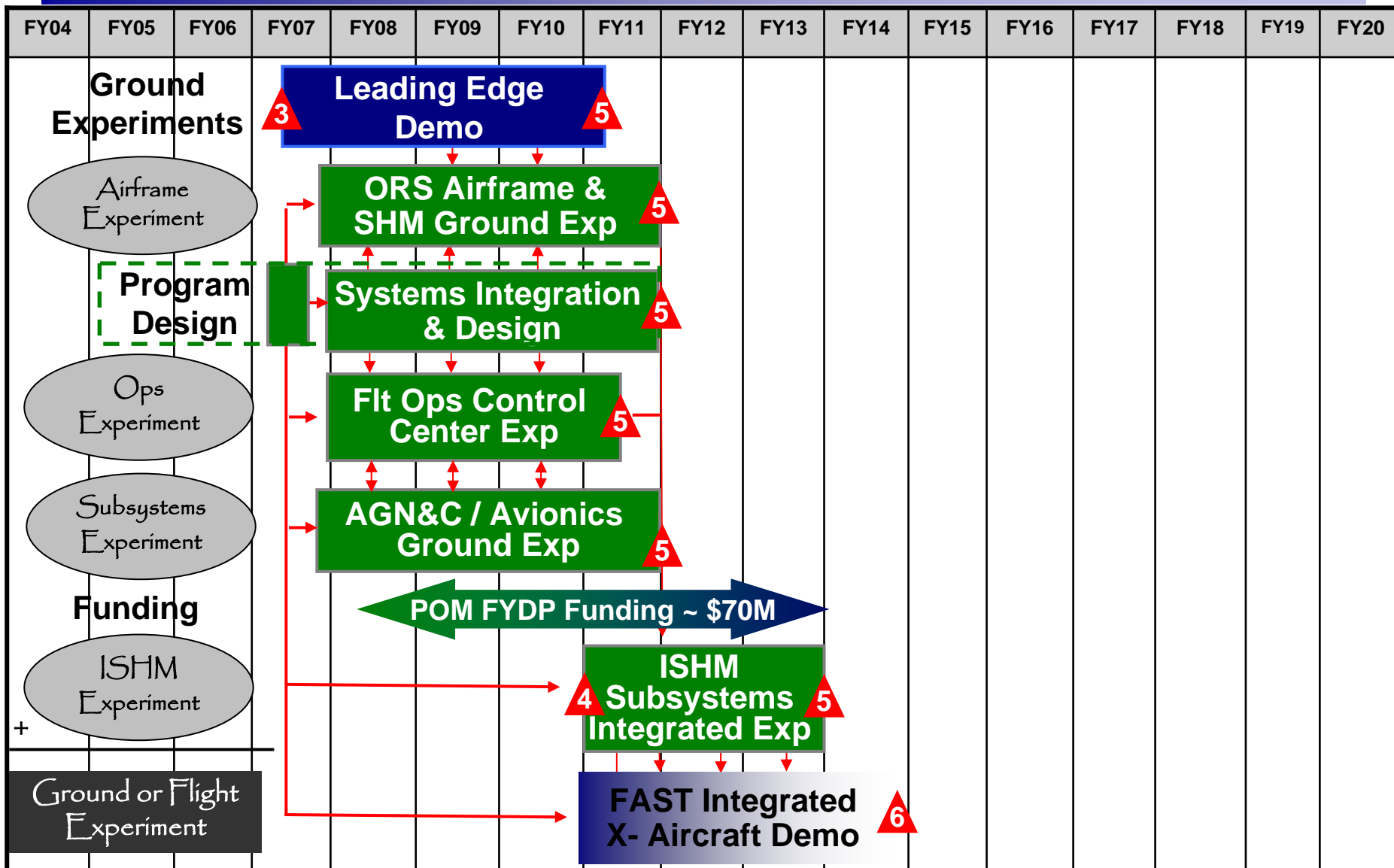
➤ **What is Fast?**

➤ **Way Ahead**

➤ **Summary**

Schedule

- Experiments Feed Future RLV Systems -



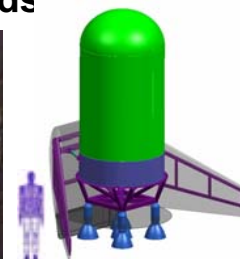
Airframe & SHM Ground Experiment

AIRFRAME PRODUCT

A full scale X-Vehicle airframe that integrates tanks, structure and TPS; and tests the integrated assembly through multiple mission cycles

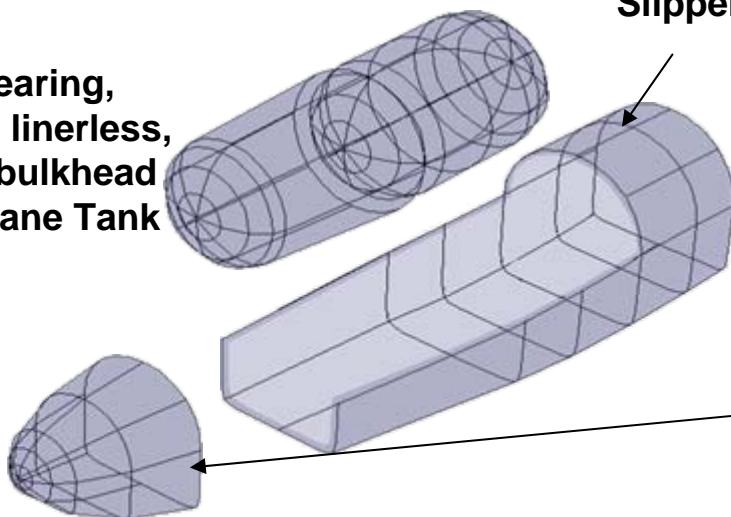
Ground Testing

High temperature ascent & reentry testing with aero-loads

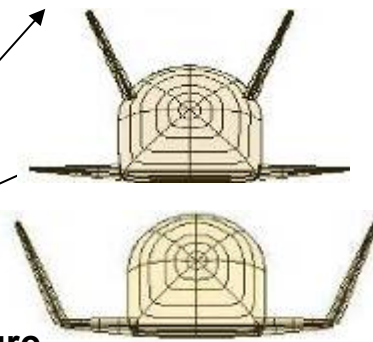


Slipper Structure

Load bearing, composite linerless, common bulkhead LOX/Methane Tank

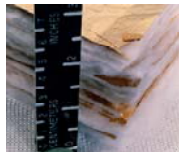


Hot Structure



External Insulation and TPS where required

Mechanically Attached AFRSI/CRI

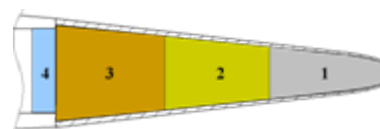


Multilayer Insulation

CMC Wrapped TUFI Tile

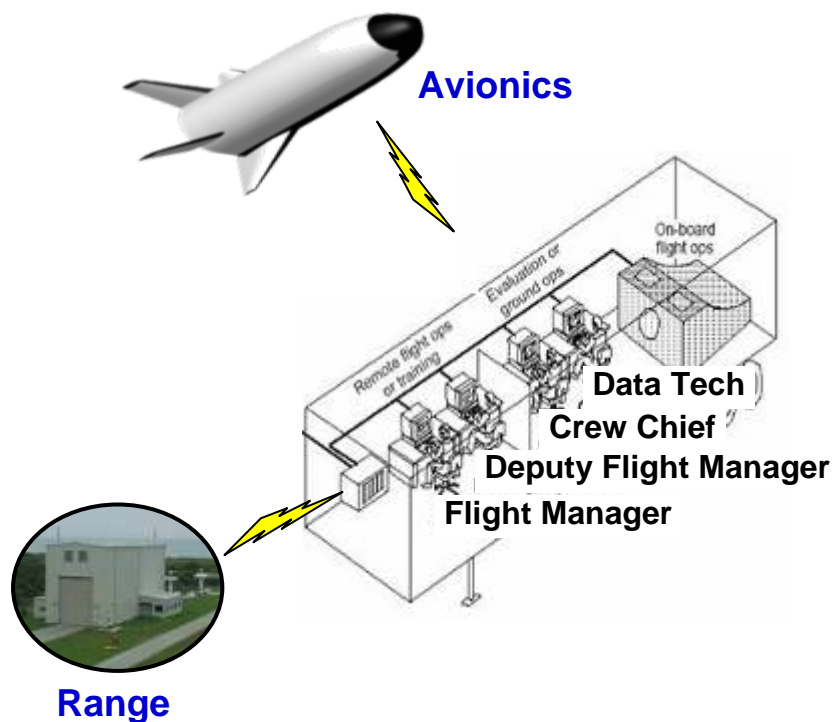


CC or CSic nose with High Thermal Conductivity CC Foam backface as req



SUBSYSTEMS PRODUCT(s)

FOCC Laboratory for Exploring CONOPS that Integrates with Additional Experiments ("Iron Bird"), including Avionics, Subsystems, Adaptive GN&C and ISHM

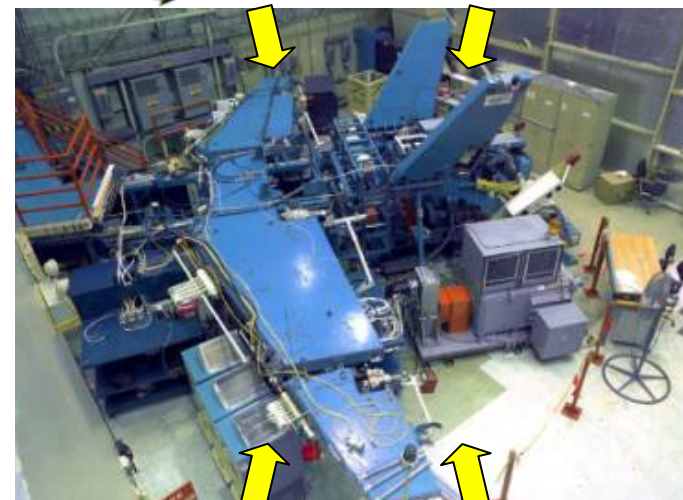


Retrofit & Test Subsystems, Adaptive GNC, & ISHM "Iron Bird" H/W & S/W

Structures



Avionics



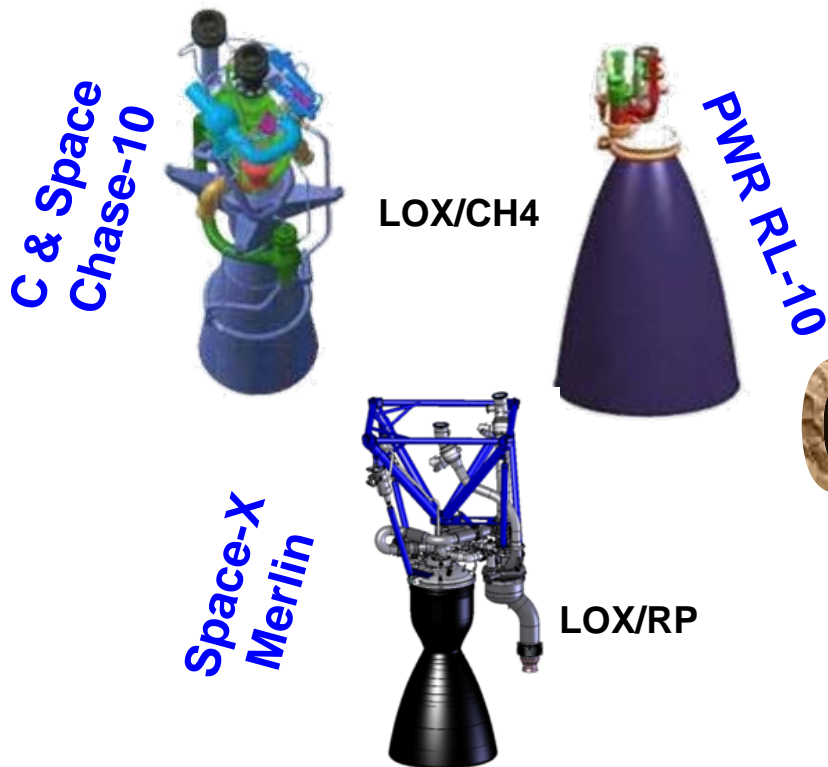
Propulsion



Flight Controls

Propulsion Options

“Off the Shelf” Engine Options



FAST will leverage existing or low risk engine options if a low cost affordable experiment is not funded

Experiment to Prove Potential for Low Cost Affordable LOX/CH4 Propulsion Options

XCOR CEV Engine



D&E Propulsion & Power



PROPULSION PRODUCT ~ Unfunded

Affordable propulsion experiment focused on LOX/HC

Integrates IPD Operability and Propulsion Health Management Advantages

Propulsion Experiment



- *Potential LOX/Methane Propellant Advantages* -

Facilitates
Common
Bulkhead
Propellant
Tank

LOX/Methane
Temp
Difference
< 40°F

Low Probability
Catastrophic
Failure

Minimizes Number
of Fluids - One
Propellant For
Main Engine
OMS/RCS/APU



Minimizes
Engine Purge
Requirements by
Cryogenic Boil Off

Autogenous
Pressurization
of Main
Propellant
Tanks

Higher
 I_{sp} than RP

Maximizes
Thrust
Chamber Life
and Reliability
Higher Coking
Limit

Potential for Enhanced Operability!

Summary



- **FAST key objective: leverage private & entrepreneurial sectors**
 - Technology feeds next generation orbital space access
- **Approach is methodical technology development**
 - Operability focus: high tempo ops, low cost, high reliability, etc.
- **Resources in place to execute FAST ground demos**
 - Airframe experiment with ATP in Sep 07
 - Subsystem experiment(s) with ATP in Sep 07
 - Integrated ground experiment with ATP in Fall 10
 - ➡ Continuing to seek flight experiment partner(s)
- **Points of contact**
 - Technical – Lt Doupe, cole.doupe@wpafb.af.mil, (937) 255-6784
 - Contracts – Mr. Poteet, Roger.Poteet@wpafb.af.mil, (937)-255-4783